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SUPPLEMENTAL IMPLANT COATED WITH HYDROXYAPATITE, AND METHODING METHOD
FOR SUPPLEMENTAL IMPLANT WITH PLASMA-SPRAYED HYDROXYAPATITE
[Suisanrin haiishi de hifuku shita hoju inpuranto oyobi suisanrin
haiishi wo purazuma supurei shita hoju inpuranto no shori hoho]

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[Claim 1] A method for the manufacture of an implant with a coating of at least 90 wt% crystalline hydroxylapatite, comprising a step for plasma spraying the implant with hydroxylapatite, a step for placing the implant in a sealable, pressurizable container, a step for heating the implant in the presence of steam inside the container, a step for cooling the implant, and a step for rinsing the implant with water.

[Claim 2] The method of Claim 1, wherein the method further comprises a step for removing carbon dioxide (CO₂) from the steam before the step for heating the implant.

[Claim 3] The method of Claim 1, wherein the heating step includes heating the implant to at least about 250°C at a final pressure of at least 270 psi.

[Claim 4] The method of Claim 1, wherein the method further comprises a step for rinsing the implant in acetone to remove the water after the rinsing step, and a step for drying the implant in air to remove the acetone.

[Claim 5] A method for treating a dental implant, wherein the method comprises a step for plasma spraying the implant with a coating of hydroxylapatite, the coating including the crystalline phase of hydroxylapatite, amorphous calcium phosphate, calcium oxide, tricalcium phosphates (including α -TCP and β -TCP) and tetracalcium phosphate, a step for heating the implant within a pressurized

* Claim and paragraph numbers correspond to those in the foreign text.

environment in the presence of water, a step for converting the amorphous calcium phosphate to crystalline hydroxylapatite, a step for converting the calcium oxide to calcium hydroxide, a step for exposing the implant to an aqueous environment, and a step for dissolving the calcium hydroxide from the coating.

[Claim 6] The method of Claim 5, wherein the method further comprises a step for removing carbon dioxide (CO_2) from the water before the step for heating the implant.

[Claim 7] The method of Claim 5, wherein the heating step includes heating the implant to a final temperature between 250 and 300°C at a final pressure between 800 and 1100 psi, and wherein the implant is maintained at the final temperature and pressure for 0 to 20 minutes.

[Claim 8] The method of Claim 5, wherein the method further comprises a steps for converting the tricalcium phosphates (including α -TCP and β -TCP) to crystalline hydroxylapatite, and a step for converting the tetracalcium phosphate to crystalline hydroxylapatite.

[Claim 9] The method of Claim 5, wherein the exposure step includes immersing the implant in water for between one and two hours.

[Claim 10] The method of Claim 5, wherein the heating step includes heating the implant until the coating has 5 wt% or less amorphous calcium phosphate.

[Claim 11] The method of Claim 5, wherein the heating step includes heating the implant until the coating has 1 wt% or less calcium hydroxide.

[Claim 12] A method for purifying a coating on an implant, wherein the method comprises a step for plasma spraying the implant with hydroxylapatite to create a first coating including both crystalline hydroxylapatite and non-crystalline hydroxylapatite, a step for hydrothermally treating the first coating at a temperature between 200°C and 300°C to convert the first coating into a second coating, a portion of the non-crystalline hydroxylapatite of the first coating being converted to crystalline hydroxylapatite to create a second coating with a greater wt% of crystalline hydroxylapatite than the first coating, and a step for leaching the second coating to convert the second coating into a final coating, the calcium hydroxide in the second coating being dissolved to create the final coating with a greater wt% of crystalline hydroxylapatite than the second coating.

[Claim 13] The method of Claim 12, wherein the steps for hydrothermally treating and leaching create a final coating with 97 wt% crystalline hydroxylapatite.

[Claim 14] The method of Claim 12, wherein the step for hydrothermally treating further consists of a step for heating the implant in a pressurized water-vapor environment, and a step for cooling the implant, and wherein the step for leaching further comprises a step for immersing the implant in water.

[Claim 15] The method of Claim 12, wherein a first portion of the non-crystalline hydroxylapatite contains tricalcium phosphates (including α -TCP and β -TCP), tetra-calcium phosphate and amorphous calcium phosphate, and wherein a second portion of the non-crystalline

hydroxylapatite contains tricalcium phosphates, tetra-calcium phosphate and amorphous calcium hydroxide.

[Claim 16] A method for treating an implant for implantation in bone to realize osseointegration, wherein the method comprises a step for preparing an implant, a step for plasma-spraying hydroxylapatite on the implant to form a first preliminary coating on the implant, a step for heating the implant and the first preliminary coating in a water-vapor environment to convert the first preliminary coating to a second preliminary coating comprising at least 90 wt% crystalline hydroxylapatite, and a step for exposing the implant and the second preliminary coating to water in the liquid state to convert the second preliminary coating to a final coating consisting of a greater percentage by weight of crystalline hydroxylapatite than the second preliminary coating.

[Claim 17] The method of Claim 16, wherein the final coating comprises 90% to 98 wt% crystalline hydroxylapatite.

[Claim 18] A dental implant comprising a substrate and a surface coating on the substrate, wherein the coating comprises plasma-sprayed hydroxylapatite with at least 95 wt% crystalline hydroxylapatite.

[Claim 19] The dental implant of Claim 18, wherein the coating is substantially free of calcium oxide and calcium hydroxide.

[Claim 20] The dental implant of Claim 18, wherein the surface coating is prepared by plasma-spraying hydroxylapatite on the substrate to form a first preliminary coating on the substrate, heating the substrate and the first preliminary coating in a water-

vapor environment to convert the first preliminary coating to a second preliminary coating with at least 90 wt% crystalline hydroxylapatite, and exposing the substrate and the second preliminary coating to water in the liquid state to convert the second preliminary coating to a final coating substantially free of calcium oxide, calcium hydroxide and calcium carbonate.

[Claim 21] An implant for implantation in bone to realize osseointegration, wherein the implant comprises a substrate and a surface coating on the substrate comprising plasma-sprayed hydroxylapatite, wherein the surface coating as determined using X-ray diffraction analysis at 20 between 16° to about 40° contains at least 90 wt% crystalline hydroxylapatite and is substantially free of calcium oxide and calcium hydroxide.

[Claim 22] The implant of Claim 21, wherein the coating is treated using a two-step method with hydrothermal treatment step followed by a leaching step.

[Claim 23] The implant of Claim 21, wherein the coating comprises 97 wt% crystalline hydroxylapatite after the substrate is heated in a water-vapor environment to a final temperature of 300°C and a final pressure of 1100 psi and maintained at the final temperature and pressure for approximately 15 minutes.

[Detailed Description of the Invention]

[0001]

[Technical Field of the Invention] The present invention relates to implantable prosthetic implants for osseointegration and methods

for treating the same and, more specifically, to implants with a hydroxylapatite coating to promote osseointegration and to methods for treating implants plasma-sprayed with hydroxylapatite.

[0002]

[Prior Art] Since the 1980s, there has been a wave of technology directed towards the manufacture of dental implants that are extremely biocompatible with human tissue and bone. One purpose of this technology has been to manufacture an implant that resembles as closely as possible natural bone tissue. This type of implant would be able to more fully integrate with existing bone tissue and promote new bone growth around the implant.

[0003] Biological apatite is one of the primary compounds in human bones and teeth. A synthetic form of this mineral, hydroxylapatite (HA), is very similar to this naturally occurring apatite. The similarity between synthetic HA and naturally occurring apatite has encouraged scientists to promote the use of HA in dental and orthopedic implants. One purpose of present research is to manufacture an implant that more readily integrates with surrounding bone and tissue after implantation.

[0004] Some of the dental implants in the first attempt at applying synthetic apatite were formed completely from sintered HA. These implants had superior bioactive properties after implantation. Scientists, however, discovered that the mechanical properties of these implants tended to be insufficient. For example, dental implants

formed solely from HA could not withstand normal physiological loads and tended to crack and break apart after implantation in patients.

[0005] Since then, research has focused on using metallic implants such as those formed with titanium substrates. Metallic implants are strong and able to withstand the physiological load occurring with the jaw bone. These implants, however, do not osseointegrate as quickly as implants formed exclusively from HA. Attention since then has been directed toward coating metallic implants with HA.

[0006] Plasma spraying is a well known method for coating metallic implants with HA. In this method, a stream of mixed gases passes through a high temperature electric arc that ionizes the gases into a plasma flame. Next, a crystalline HA feedstock powder is supplied to the stream and deposited in molten state on the outer surface of the implant. The spray adheres to the surface and forms a relatively thin coating of HA.

[0007] HA coated metallic implants manifest the advantages of completely metallic implants as well as completely HA implants. In other words, these implants are strong and bone tissue forms a strong bond with the coating surface to promote biocompatibility and osseointegration. Unfortunately, there are several significant disadvantages associated with plasma spraying.

[0008] Plasma spraying exposes HA to extremely high temperatures which causes undesirable changes in morphology and chemical composition. These changes cause particular problems. In particular,

highly crystalline HA is known to have in vitro stability that is much higher than non-crystalline HA. A high quality HA material is completely crystalline before it is sprayed. The temperatures associated with plasma spraying, however, cause the HA to partially transform from a pure and crystalline form to a much less crystalline structure. This non-crystalline HA is commonly known as amorphous calcium phosphate (ACP). During plasma spraying, crystalline HA material is also partially converted into other crystalline compounds such as tricalcium phosphate (including α -TCP and β -TCP), tetracalcium phosphate (TTCP) and calcium oxide (CaO). These impurities can be called crystalline soluble phases because their solubility in aqueous solutions is substantially higher than that of crystalline HA.

[0009] Impurities resulting from plasma spraying HA cause several problems. First, these impurities tend to dissolve into the surrounding tissue. In other words, the plasma-sprayed coating on the implant disintegrates over time and some of the coating is lost. If the HA coating dissolves, the bioactive interface between the bone and the implant is believed to become less effective. The dissolution of the coating may even weaken the interface between the implant and the surrounding bone and, more particularly, the interface between the coating and the implant. Moreover, some of these impurities have a hemolytic effect in vitro. CaO, in fact, has been shown to cause hemolysis. Considerable attention has therefore been given to converting the impurities in the coating back into crystalline HA.

[0010] Heat treatment is one method used to restore the highly crystalline structure of HA plasma-sprayed coatings. In this method, the coated implant is heated in air to a relatively high temperature, usually between 500 and 600°C. The high temperature recrystallizes some of the amorphous HA and also converts some of the soluble phases into crystalline HA. Unfortunately, the high temperature also lowers the fatigue strength of the titanium alloy substrates. Heat treatment is thus not a suitable method because implants need to maintain their strength and structural integrity.

[0011] Hydrothermal treatment is another method used to obtain highly crystalline HA. The temperature during treatment is, advantageously, lower than the temperature required in the heat treatment method. As a result, the metallic substrate does not break down.

[0012] Some types of hydrothermal treatments are conducted in an autoclave. HA coated implants can be placed inside an autoclave in the presence of water or an aqueous solution. The temperature and pressure are then increased inside the autoclave. As the temperature rises, the water turns to steam thereby elevating the pressure. The implants are kept at this temperature and pressure while the amorphous and soluble crystalline phases are converted into crystalline HA.

[0013] One disadvantage of current hydrothermal treatments is the relatively high percentage of impurities in treated implants including amorphous and soluble crystalline phases. For example, some of the ACP does not recrystallize. As a result, an implant with extremely high

crystalline HA content cannot be obtained. Dental implants with high crystallinity are preferred for implantation.

[0014] Another disadvantage is that the long treatment time required in the hydrothermal method. Some hydrothermal treatments require that the implant be exposed to high temperature and pressure for several hours and even days. In other words, these methods cannot be used to treat a large quantity of implants in a short period of time.

[0015] Another disadvantage is that current hydrothermal methods do not affect all impurities present after plasma spraying. This results in a treated implant with higher amorphous and soluble crystalline phase content than in other methods. Therefore, a relatively high percentage of impurities remain when the treatment is completed.

[0016] Another disadvantage is that some hydrothermal methods require a relatively high temperature. Higher temperatures, as mentioned above with reference to heat treatment, reduce the strength of the metallic substrate.

[0017] Another disadvantage is that some hydrothermal methods require extreme operating conditions such as high pressure. Devices able to handle extremely high pressurize environments are expensive and also impractical from the standpoint of manufacturing large quantities of treated implants.

[0018] Yet another disadvantage is that some hydrothermal methods require the immersion of implants in an aqueous solution for an

extended period of time, lasting many hours and even days. These methods are used to selectively dissolve non-HA components and leave the desirable materials intact. Immersing the implants in this way, however, can negatively affect the strength of the adhesive coating, weaken the tensile strength of the implant, and cause other undesirable side effects.

[0019] Still another disadvantage is that some hydrothermal methods using a water-vapor environment in which the water contains carbon dioxide (CO_2). This carbon dioxide reacts with the HA coating on the implant to form calcium carbonate (CaCO_3).

[0020]

[Constitution of the Invention] The present invention relates to dental implants and orthopedic prostheses with a highly crystalline hydroxylapatite (HA) coating. The implant is first coated with HA using any well known plasma spraying technique. After the implant has been plasma-sprayed with HA, it is subjected to a two-step method consisting of a hydrothermal treatment step and a leaching step. These two steps can be used to obtain an implant with a highly crystalline HA coating containing only a small percentage of amorphous calcium phosphate (ACP). The coating is also substantially free of calcium hydroxide, calcium oxide, and calcium carbonate.

[0021] In the hydrothermal treatment step, the implant is placed inside a container or device able to handle high temperature/high pressure environment. The implant is then heated under pressure in the presence of a water vapor environment. When the desired temperature is

reached, it is maintained for a predetermined amount of time. The container or device is then ventilated, and the implant is allowed to cool. Next, the implant is treated in the leaching step. This step includes exposing the implant to water in liquid form for a predetermined period of time. The implant is then exposed immediately to an organic solvent such as acetone and then allowed to dry in the air.

[0022] One advantage is that the treated implant has a coating with a high percentage of crystalline HA. As a result, ACP and soluble crystalline phase impurities are completely or almost completely converted into crystalline HA or dissolved in the coating. For example, the surface coating can be 97 wt% crystalline HA.

[0023] Another advantage is that the overall processing time required to treat the implant after plasma spraying is relatively short. The processing time for both the hydrothermal treatment step and the leaching step can be as short as several hours. As a result, more implants can be cycled through the process in a predetermined time period.

[0024] Another advantage is that the method can treat a large quantity of crystalline impurities. After plasma spraying, the coating sometimes contains calcium oxide. In the hydrothermal treatment step, this calcium oxide does not fully convert into crystalline HA. Instead, some of the calcium oxide converts into calcium hydroxide. Calcium hydroxide dissolves during the leaching step. As a result, the treated implant contains neither calcium oxide nor calcium hydroxide.

[0025] Another advantage is that the hydrothermal treatment step in the present invention does not require a very high temperature. As a result, the strength of the metallic substrate does not deteriorate.

[0026] Another advantage is that the hydrothermal treatment step does not require extreme pressure in order to obtain an implant with a highly crystalline HA coating. Under certain operating conditions, the pressure can be set between 250 psi and 1100 psi to obtain a surface coating of at least 90 wt% crystalline HA. As a result, a device capable of withstanding impractically high pressures is not required. Yet another advantage is that the leaching step can be performed in about two hours. As a result, the implants are not immersed in water or an aqueous solution long enough to affect negatively the adhesive strength of the coating, weaken the tensile strength of the implant or result in any other undesirable side effect.

[0027] Still another advantage is that dissolved carbon dioxide is removed from the water before the implant is treated in a water-vapor environment in the hydrothermal treatment step. As a result, carbon dioxide does not react with the HA coating to form calcium carbonate.

[0028] The present invention includes devices and methods with the structures, combinations of structures and arrangement of components explained in detail below. The following is a detailed explanation of the essence and purpose of the present invention with reference to the attached figures.

[0029] FIG 1 shows a reaction vessel 10 used to perform the method of the present invention. The reaction vessel 10 can be any device known in the art that is able to create a high pressure/high temperature environment, such as an autoclave or pressurizable container or chamber. The reaction vessel 10 comprises a thick-walled, substantially cylindrical pressurizable container 12 consisting of a base 14 and a cover 16. The base 14 has a cylindrical side wall 18 defining a cylindrical cavity 20 inside. The cavity 20 is open at the top of the base 14 and is closed at the bottom end. A flat bottom wall 22 is integrated with the side wall 18 to form the bottom enclosure. A ring-shaped flange 24 integrates with and extends outward radially from the side wall 18 to form the top portion of the base 14. The walls of the container 12 are made of a material of sufficient strength and biocompatibility to provide a cavity able to sustain high temperature/high pressure environment. For example, these walls can be made of 316 stainless steel to create a cavity 20 with a volume of 276 cm³.

[0030] The cover 16 is usually a flat disk designed to fit tightly against the ring-shaped flange 24. A heat-resistant gasket (not shown) such as a graphite gasket is installed between the cover 16 and the flange 24 to form an air tight seal. A plurality of circumferentially spaced holes (not shown) extend through the cover 16 into flange 24. A plurality of corresponding threaded bolts 26 are fitted into these spaced holes. As the bolts 26 are tightened, they

subject the cover 16 to pressure and compress the gasket between the cover and the flange 24 to create an air tight seal for the cavity 20.

[0031] A plurality of conduits 30, 32, and 34 pass through cover 16. These conduits are sealed to the cover and communicate with the cavity 20 to provide a route for the introduction and discharge of gas or some other fluid. Each conduit 30, 32, 34 is provided with a valve 36, 38, and 40, respectively, for stopping or controlling the flow of the gas or fluid. The outer end 42 of conduit 30 has a vent 44, and the outer end 46 of conduit 32 has an inlet 47 that attaches to the source (not shown) of an ultra pure inert gas such as helium or argon. The gas flows through conduit 32 into cavity 20 and is then discharged from the cavity via conduit 30. The outer end 48 of conduit 34 has a gauge 50 for measuring the gas pressure inside cavity 20.

[0032] A thermal well 52 passes through the cover 16 and is sealed with respect to the cover 16. The well comprises a conduit with a first end 54 extending into cavity 20 and a second end 56 communicating with the exterior of the pressure container 12. The well 52 is closed at end 54 to prevent communication of the gas or fluid with the exterior of container 12 via the conduit. As shown in the figure, end 54 extends into the cavity 20 to establish thermal communication with the interior of the cavity. Sufficient space exists between end 54 and the interior sidewalls of the cavity 20 to maintain proper insulation for recording thermal measurements.

[0033] An electric thermocouple 55 is installed in end 54 and exposed to the temperature inside the cavity 20. The thermocouple

generates an electrical voltage proportionally related to the temperature inside the cavity. The thermocouple comprises two wires forming a junction that extend the length of well 52 and connect to a proportional integral differential (PID) control device (not shown). The control device converts the electrical voltage generated in this way to a convenient temperature scale for display and controls the operation of a heat source for the reaction vessel 10. An appropriate PID control device for this application is Model 942 manufactured by Watlow of Winona, Minnesota, USA.

[0034] A removable reservoir 60 is also installed inside the cavity 20. The reservoir consists of a cylindrical container with an open top 62. Purified water in liquid state is kept in reservoir 60 and exposed to the interior space of the cavity 20.

[0035] An electric heating jacket 64 surrounds the exterior of the container and is used to heat the interior of the cavity 20. During the heating process, thermocouple 55 senses the temperature inside the cavity, and sends the temperature to the PID control device. As the temperature inside the cavity approaches a predetermined value, the control device reduces the rate at which the heating jacket 64 provides heat or stops providing heat in order to prevent an overshoot of the desired temperature.

[0036] A ceramic insulating material 66 surrounds the container 12 and the heating jacket 64. The blanket preferably has a thickness of at least about one inch and has a density of approximately eight pounds per cubic foot, which is enough to insulate the container.

[0037] FIG 2 shows another reaction vessel 100 used to conduct the method of the present invention and shows in greater detail the system used to regulate the operations of the reaction vessel.

[0038] The reaction vessel 100 usually has a thick-walled, pressurizable container 102 consisting of a base 104 and a cover 106. The base 104 and the cover 106 define a cavity 108. This cavity can be accessed by removing the cover 106 from the base 104. A heater 110 heats the cavity 108 to the predetermined temperature during operations.

[0039] The cover 106 is designed to fit tightly against the base 104. A heat resistant gasket (not shown) is installed between the cover 106 and the base 104 to form an air tight seal. A plurality of bolts (not shown) pass through the cover and the base to produce an air tight seal for the cavity 108.

[0040] A plurality of conduits and lines form a portion of the reaction vessel 100. These conduits and lines regulate and maintain the operations of the reaction vessel as explained in more detail below.

[0041] A water line 120 extends through the cover 106 to a plurality of cooling coils 122. These coils extend into the cavity 108 and connect to the external drain line 123 providing outlet for the cooling coils. Line 120 contains a flow meter 124 and a valve 126. The flow meter 124 measures the flow of water through line 120. The flow of the water can be controlled using a valve 126.

[0042] A compressed air line 130 connects to the water line 120 and also communicates with the cooling coils 122. The line 130 includes a compressor 132, an air regulator 134 and a valve 136. The compressor 132 compresses incoming filtered air. This compressed filtered air passes through regulator 134 which regulates and controls the flow of air. The air flow can be adjusted using a valve 136.

[0043] An argon gas line 140 extends through the cover 106 and communicates with the cavity 108. A gas regulator 142 regulates the flow of gas into the line 140. After leaving the regulator, the gas passes on to a flow meter 144 for measuring and controlling the flow rate. It then passes through two valves 146, 148. The two valves adjust the flow of gas through the line 140. In addition, a pipe 150 extends from air line 130 and connects to gas line 140. This pipe also includes a valve 152.

[0044] A system of valves communicating with the air and gas lines controls the flow of gas into the cavity 108. If valves 152, 148 are open and valve 146 is closed, compressed air can flow into the cavity 108 but gas is kept out. If valves 146 and 148 are open and valve 152 is closed, gas can flow into the cavity 108 but air is kept out.

[0045] During operation of the reaction vessel 100, the pressure, temperature, and steam inside the cavity 108 are closely monitored and controlled. A vent line 160 extends through the cover 106 and includes a valve 162. When the valve 162 is open, the line 160 can be used to release steam or purge gas from the cavity 108.

[0046] A safety line 164 also extends through the cover 106 to communicate with the cavity 108. This line 164 includes a rupture disk 166 that prevents an excess build up of pressure within the cavity 108. If a dangerous level of pressure occurs inside the cavity, the disk 166 ruptures and vents the built-up pressure via the line 164.

[0047] As shown in the figure, a pressure line 170 extends through the cover 106 to the cavity 108 and includes two pressure transducers 172, 174. Transducer 172 measures the pressure inside the cavity 108. It can be, for example, an analog gauge. Transducer 174 also measures the pressure inside the cavity 108 and can be an electrical transducer device. In addition, a process pressure indicator 176 communicates with transducer 174 and has a digital pressure display.

[0048] A thermowell 180 extends into the cavity 108. This well includes a thermocouple 182 and is connected to a process temperature control device 184. This control device has a digital display showing the temperature inside the cavity 108 and can be programmed to control the heating parameters such as the heating time, the hold time, and the temperature. As shown in the figure, the indicator 176 and the control device 184 are connected to a chart recorder 186. This recorder records both pressure and temperature and maintains historical data.

[0049] Yet another thermocouple 190 communicates with the cavity 108. This thermocouple connects to a surface temperature control device 192 and keeps the temperature from getting too high inside the

cavity 108. The control devices 184, 192 are connected to a power source 194. This power source can also be used to power the heater.

[0050] FIG 3 shows the overall process in the present invention. This process usually consists of a hydrothermal treatment step followed by a leaching step.

[0051] In block 200, the implants are prepared. Next, in block 202, the implants are coated with HA. Plasma spraying is used to coat the implants. Any coating technique well known in the art can be used. HA powder is used in the spraying method and preferably has a crystalline HA content close to 100%. When the implants have been sprayed, the coating consists of crystalline HA and various impurities such as ACP and soluble crystalline phases. The percentage of impurities varies depending on a number of factors, such as the crystallinity of the HA used and the parameters during plasma spraying.

[0052] When the implants have been sprayed, they are ready for the hydrothermal treatment step shown in block 204. This step is described in detail in block 206 through block 212.

[0053] In block 206, the reaction vessel is prepared. At this time, the implants are sealed in the container and the predetermined processing parameters are set. Some of the processing parameters include, for example, replacing the air inside the container with an inert gas such as helium or argon, setting the amount of water in the container, setting the rate at which the implants are to be heated and

cooled, setting the maximum pressure and temperature, and setting the hold time for the predetermined pressure and temperature.

[0054] Any dissolved carbon dioxide (CO_2) should be removed from the water in the container before the heat treatment is started. Carbon dioxide reacts with the HA coating on the implant, specifically with CaO or $\text{Ca}(\text{OH})_2$ to form calcium carbonate (CaCO_3). Several different methods can be used to remove carbon dioxide from water, and these methods are well known in the art. Examples include boiling the water, bubbling gas (such as helium) through the water (a method called gas sparging), or treating the water with a deionizer.

[0055] In block 208, the implants are heated to the predetermined temperature. At this time, the pressure inside the container increases and the water undergoes a phase shift from liquid to saturated steam.

[0056] Next, in block 210, the implants are maintained at the maximum temperature and pressure for a predetermined period of time. For example, the implants can be held for 15 minutes at 300°C and a pressure of 1100 psi. Afterwards, the steam is ventilated, and the container and implants are cooled as shown in block 212.

[0057] When the hydrothermal treatment step has been completed, the implants should be at least 90 wt% crystalline HA. The calcium oxide present after plasma spraying is converted into calcium hydroxide.

[0058] The leaching treatment begins in block 214. The leaching treatment removes unwanted calcium hydroxide from the coating and

leaves a coating consisting substantially of crystalline HA and a small amount of ACP.

[0059] In the leaching treatment, the implants are exposed to water as shown in block 216. The water dissolves the calcium hydroxide in the coating. One method that can be used to expose the implants to water is to immerse them in water in a liquid state. The water should be agitated (e.g., stirred) and the implants should be kept in contact with the water for as long as two hours. This period of time should be long enough to dissolve as much of the calcium hydroxide as practical without subjecting the implants or coating to any undesirable side-effects.

[0060] After the implants have been exposed to water, they are immediately exposed to dry acetone as shown in block 218. The acetone removes any water remaining on the implants. The implants can be immersed in an acetone bath for about 60 seconds. Immersion into successive acetone baths may be necessary to completely remove the residual water from the implants.

[0061] Finally, in block 220, the implants are allowed to dry in the open air. During the drying process, the acetone evaporates from the coating.

[0062] After the hydrothermal treatment and leaching treatment steps have been completed, the implants should consist of a substrate with a coating of highly crystalline HA. The coating should contain 90 wt% to 100 wt% crystalline HA and be substantially free of calcium

oxide, calcium hydroxide, calcium carbonate, and soluble crystalline phases.

[0063] Returning to FIG 1, a preferred mode for embodying the present invention will now be explained in greater detail. Hydroxylapatite is plasma-sprayed on to the exterior of an implant such as a dental implant or an implantable prosthesis. Several plasma spraying techniques are well known in the art. After the implant has been HA coated, the cover 16 is removed from the flange 24 and the implant is placed inside the cavity 20 of the container 12. A plurality of implants can be placed inside the cavity on racks (not shown) to prevent direct contact with any wall or surface inside the container 12. A predetermined amount of purified water in the liquid state is then placed in reservoir 60. This water should be treated to remove carbon dioxide using any method common in the art, such as boiling, helium sparging or de-ionization. The reservoir keeps the liquid water from making direct contact with the implants. The cover 16 is placed on the flange 24, and the bolts 26 are tightened to place cover 16 tightly over flange 24 and create a good air-tight seal. After the container 12 has been closed, valves 36 and 38, serving as the vent valve and gas supply valve, respectively, are opened. A source of ultra pure inert gas, preferably helium or argon, is allowed to flow through the valve 38 and into the cavity 20. The flow of gas that displaces the original air environment inside the cavity 20 is via vent valve 36. This flow of gas is maintained long enough to purge the cavity 20 of air and create a completely inert environment. The

elimination of air minimizes oxidation of the titanium substrate which discolors exposed metal surfaces. A purging process that lasts about fifteen minutes at a gas flow rate of 1,770 cc/min. has been found to be satisfactory for reaction vessels.

[0064] After the purging has been completed, the vent valve and gas supply valve are closed to seal the inert gas environment inside the cavity 20 at a pressure equal to atmospheric pressure. The heating jacket is activated to start heating the cavity 20. Over the next 60 minutes, the interior temperature of the cavity 20 rises from room temperature to a final temperature of 300°C. The liquid water in the reservoir 60 undergoes a phase shift from liquid to gas to generate a final pressure inside the cavity of approximately 1100 psi.

[0065] The temperature is maintained at 300°C for about 15 minutes. Afterward, valve 36 is opened and the steam is ventilated into the outside environment. This results in an immediate drop of pressure and temperature. The valve 36 is then closed to keep air from entering the container 12. The container 12 is removed from the heating jacket 64 and allowed to cool until the cover 16 can be safely removed without any risk of warping or damage to the container. Cooling the container to a temperature of 100°C over the course of 45 minutes has been found to be satisfactory.

[0066] After it has cooled, the container 12 is opened and the implant or rack of implants is removed from the cavity 20. The implant or rack is then immersed in distilled water at room temperature for about two hours. Preferably, the water is stirred or the rack is

rocked in order to generate relative motion between the implants and the water. The implants are then removed from the distilled water and immediately immersed in a first acetone bath for about 30 seconds. The rack and implants are then withdrawn from the first acetone bath and immediately immersed in a second acetone bath for about 30 seconds. The acetone baths substantially remove the liquid water from the implants and allow them to dry quickly in air.

[0067] The processing steps described above produce a hydroxylapatite coating that is 97% crystalline hydroxylapatite and substantially free of calcium oxide, calcium hydroxide, soluble crystalline phases and CaCO_3 . The composition of the resulting coating was determined using X-ray diffraction analysis at 20 from about 16° to about 40° . The metallic substrate exhibited no significant discoloration caused by oxidation. Also, no significant decrease in adhesive strength was observed between the coating and the substrate. The preferred mode for carrying out the invention was described above, but other processing parameters and combinations can be applied within the scope of the invention. These method parameters include, for example, the initial amount of water in the reservoir, the temperature inside the cavity, the pressure inside the cavity, the hold time for the pressure and the temperature, and the length of time the implants are subjected to leaching. However, one important advantage of the present invention is that the method yields a hydroxylapatite coating that is 90 wt% to 97 wt% pure. The coating is also substantially free of calcium oxide, calcium hydroxide, soluble crystalline phases and

CaCO₃. Therefore, although the processing parameters in the hydrothermal and leaching steps can be altered, the resulting implants should at least have a 90% crystalline HA coating.

[0068] The working examples described below show some combinations that can be used for the processing parameters. The reaction vessel described in FIG 1 was used in each one of the working examples. The treated implants in the following working examples are titanium alloy strips (Ti6Al4V) coated with hydroxylapatite powder using a plasma spray method. Although the material used in the plasma spray operation was nearly 100% crystalline hydroxylapatite, immediately after spraying the coating consisted of crystalline hydroxylapatite and impurities such as amorphous phases (ACP), soluble crystalline phases, tricalcium phosphate (including α -TCP and β -TCP), tetracalcium phosphate (TTCP), and calcium oxide (CaO). The compositions of the plasma-sprayed coatings prior to treatment contained the following components: 28% to 46% crystalline hydroxylapatite, 40% to 52% non-crystalline hydroxylapatite (ACP), and 12% to 19% crystalline soluble components, including α -TCP, β -TCP, TTCP and CaO. The CaO ranged between about 0.4% and 2.0%. The HA crystallinity in all of these coatings is the lower-end crystallinity typically found in commercially available implants. The coating thickness in these samples was 0.004-0.005 inches, which is roughly twice the thickness of commercially available implants. The x-ray diffraction method used to analyze the composition of the coatings has been described by LeGeros, John P., et al. in ASTM STP 1196.

[0069]

[Working Examples]

(Working Example 1) Titanium alloy implants were plasma-sprayed with HA and then placed inside a reaction vessel 10. The reaction vessel was then filled with 20.4 g of water, closed and purged with very pure helium for 15 minutes at a rate of 400 cc/min. Heating was then conducted. After 59 minutes, the interior of the cavity 20 had reached a temperature of 282°C and a pressure of 925 psi. The reaction vessel 10 was then lowered to atmospheric pressure and removed from the heating jacket 50 [sic] [Translator's note: could be "heating mantle 50"]. X-ray diffraction analysis of the treated implants showed that the coating contained 94.5% crystalline hydroxylapatite, 4.7% amorphous calcium phosphate, and 0.8% Ca(OH)_2 . No traces of TCP, TTCP or CaO were detected. The treated implant was then stirred in distilled water for two hours at room temperature and twice dipped in acetone for thirty seconds. X-ray diffraction analysis showed that the steam-treated implant contained 0.4% Ca(OH)_2 .

[0070] (Working Example 2) Titanium alloy implants were plasma-sprayed with HA and then placed inside a reaction vessel 10. The reaction vessel was then filled with 10.0 g of water, closed and purged with ultra pure helium for 15 minutes at a rate of 400 cc/min. Heating was then conducted. After 40 minutes, the interior of the cavity 20 had reached a temperature of 300°C and a pressure of 390 psi. The reaction vessel 10 was then lowered to atmospheric pressure and removed from the heating jacket 50. X-ray diffraction analysis of

the treated implants showed that the coating contained 70.6% crystalline hydroxylapatite, 25.8% amorphous calcium phosphate, 3.0% Ca(OH)_2 and 0.7% CaO . No traces of TCP or TTCP were detected. The treated implant was then stirred in distilled water for two hours at room temperature and twice dipped in acetone for thirty seconds. X-ray diffraction analysis showed that the steam-treated implant contained 1.2% Ca(OH)_2 and 0.5% CaO .

[0071] (Working Example 3) Titanium alloy implants were plasma-sprayed with HA and then placed inside a reaction vessel 10. The reaction vessel was then filled with 23 g of water, closed and purged with ultra pure helium for 15 minutes at a rate of 400 cc/min. Heating was then conducted. After 59 minutes, the interior of the cavity 20 had reached a temperature of 170°C. The temperature was maintained at 170°C for 135 minutes, and the pressure was measured at 160 psi. The reaction vessel 10 was then lowered to atmospheric pressure and removed from the heating jacket 50. X-ray diffraction analysis of the treated implants showed that the coating contained 88.0% crystalline hydroxylapatite, 10.8% amorphous calcium phosphate, and 1.1% Ca(OH)_2 . No traces of TCP, TTCP or CaO were detected. The treated implant was then stirred in distilled water for two hours at room temperature and twice dipped in acetone for thirty seconds. X-ray diffraction analysis showed that the steam-treated implant contained 0.3% Ca(OH)_2 .

[0072] (Working Example 4) Titanium alloy implants were plasma-sprayed with HA and then placed in inside a reaction vessel 10. The reaction vessel was then filled with 12.3 g of water, closed and

purged with ultra pure helium for 15 minutes at a rate of 400 cc/min. Heating was then conducted. After 44 minutes, the interior of the cavity 20 had reached a temperature of 206°C. The temperature was maintained at 206°C for 45 minutes, and the pressure was measured at 250 psi. The reaction vessel 10 was then lowered to atmospheric pressure and removed from the heating jacket 50. X-ray diffraction analysis of the treated implants showed that the coating contained 90.2% crystalline hydroxylapatite, 8.8% amorphous calcium phosphate, and 0.9% Ca(OH)_2 . No traces of TCP, TTCP or CaO were detected. The treated implant was then stirred in distilled water for two hours at room temperature and twice dipped in acetone for thirty seconds. X-ray diffraction analysis showed that the steam-treated implant contained 0.6% Ca(OH)_2 .

[0073] (Working Example 5) Titanium alloy implants were plasma-sprayed with HA and then placed inside a reaction vessel 10. The reaction vessel was then filled with 20 g of water, closed and purged with ultra pure helium for 15 minutes at a rate of 400 cc/min. Heating was then conducted. After 60 minutes, the interior of the cavity 20 had reached a temperature of 300°C. The temperature was maintained at 300°C for 15 minutes, and the pressure was measured at 1100 psi. The reaction vessel 10 was then lowered to atmospheric pressure and removed from the heating jacket 50. X-ray diffraction analysis of the treated implants showed that the coating contained 97.0% crystalline hydroxylapatite, 3.0% amorphous calcium phosphate, and 0.0% Ca(OH)_2 . No traces of TCP, TTCP or CaO were detected. The treated implant was

then stirred in distilled water for two hours at room temperature and twice dipped in acetone for thirty seconds. X-ray diffraction analysis showed that the steam-treated implant contained 0.0% Ca(OH)₂.

[0074] The processing parameters for these working examples are shown in the following table. As demonstrated in these working examples, specific processing parameters are required to produce HA coatings with the desired chemical composition and crystalline content.

[0075]

[Table 1]

A	パラメータ	実例 M				
		1	2	3	4	5
B	ヘリウム	400cc/分	400cc/分	400cc/分	400cc/分	400cc/分
C	掃気速度					25cc/min
	ヘリウム	15分	15分	15分	15分	15分
D	水の量	20.4g	10.0g	23.6g	12.3g	20g
E	加熱時間	50分	40分	50分	44分	50分
F	最終温度	282℃	309℃	179℃	206℃	309℃
G	最終圧力	925 psi	380 psi	160 psi	250 psi	1100 psi
H	保持時間	0分	0分	135分	45分	15分
I	H ₂ O	2時間	2時間	2時間	2時間	2時間
J	液相成分	液相組成物 R				
		プラズマプレー後 → 熱/蒸気処理後 S				
K	結晶性 HA	45.3→94.5	28.8→70.5	44.8→88.0	46.2→90.2	X→97.0
	ACP	22.0→4.7	52.3→23.3	42.1→10.5	40.0→3.8	X→3.0
	TCP	7.6→6.0	9.0→0.0	7.8→0.0	7.6→3.0	X→0.0
	TTCP	4.7→0.0	8.0→0.0	5.3→0.0	5.7→0.0	X→0.0
L	液相成分	液相組成物 T				
		プラズマプレー後 → 熱/蒸気/浸出処理後 U				
	CaO	0.4→0.6	2.6→0.5	0.8→0.0	0.6→0.0	X→0.0
	Ca(OH) ₂	0.0→0.0	0.0→1.2	0.0→0.3	0.0→0.6	X→0.0

Key: A) Parameters; B) Helium Scavenging Rate; C) Scavenging Time; D) Amount of Water; E) Heating Time; F) Final Temperature; G) Final Pressure; H) Maintenance Time; I) H₂O Rinsing Time; J) Coating Components; K) Crystalline HA; L) Coating Components; M) Working Examples; N) cc/min.; O) Preferred; P) min.; Q) hrs.; R) Coating Composition; S) After Plasma Sprayed → After Heat/Steam Treated;

T) Coating Composition; U) After Plasma Sprayed → After Heat/Steam/Immersion Treated

[0076] The following working example is used to explain a preferred combination for the operating parameters of the reaction vessel described in FIG 2. The implants in this working example have characteristics similar to those described with respect to FIG 1.

[0077] (Working Example 6) Titanium alloy implants were plasma-sprayed with HA and then placed in a reaction vessel 100. The reaction vessel was then filled with 200 cc of water, closed, and purged with ultra pure argon for 20 minutes at a rate of 17.7 lpm. The water was allowed to boil for 15 minutes and then heating was initiated. The cavity interior reached a temperature of 300°C, and was maintained there for 10 minutes. The reaction vessel 100 was then lowered to atmospheric pressure and removed from the heating jacket 50. Next, the treated implant was stirred in distilled water at a rate of 50 rpm for two hours at room temperature and then dipped twice in acetone, first for one minute and then for five minutes.

[0078] Testing was performed three separate times at these processing parameters. The results from each test are shown in the following table.

[0079]

[Table 2]

A 被覆成分	初期から最終の組成 (%) D		
	第1回 E	第2回 F	第3回 G
B 結晶性HA	76.8→95.3	79.7→96.1	74.4→97.6
ACP	13.7→4.7	12.0→3.9	17.8→2.0
β -TCP	2.1→0.0	1.9→0.0	2.1→0.0
α -TCP	0.7→0.0	0.3→0.0	0.5→0.0
TTCP	5.9→0.0	5.1→0.0	4.5→0.0
CaO	1.0→0.0	0.9→0.0	0.7→0.0
Ca(OH) ₂	0.0→0.0	0.0→0.0	0.0→0.3
CaCO ₃	0.0→0.0	0.0→0.0	0.0→0.0
C 平均	結晶性HA : 77.0→96.3 H		
	ACP : 14.5→3.5		
	可溶性層 : 5.8→0.1 I		

Key: A) Coating Compositions; B) Crystalline HA; C) Average;
D) Compositions From Start to End (%); E) 1st; F) 2nd; G) 3rd;
H) Crystalline HA; I) Soluble Layer

[0080] The third test yielded the preferred results and shows that the coating on the treated implant contained 97.6% crystalline hydroxylapatite, 2.0% amorphous calcium phosphate, and 0.3% Ca(OH)₂. No traces of TCP, TTCP, CaO or CaCO₃ were detected.

[0081] In the working examples, the temperature ranged between 170°C and 300°C. It should be clear to those skilled in the art that higher temperatures result in a more crystalline coating.

[0082] FIG 4 shows a typical dental implant 300 treated using the method of the present invention. This dental implant 300 has a substantially cylindrical, elongated substrate 302 consisting of a biocompatible titanium alloy. The outer surface 304 of the substrate 302 is coated with an adhesive layer 306 consisting substantially of crystalline hydroxylapatite. This layer 306 usually comprises at least 90 wt% crystalline hydroxylapatite, preferably 95 wt% crystalline

hydroxylapatite and ideally 97 wt% crystalline hydroxylapatite. Preferably, the layer 306 is also substantially free of calcium oxide in addition to being substantially free of calcium hydroxide and calcium carbonate. Here, 'substantially free' means no more than 1 wt% in the crystalline soluble phases.

[0083] It should be noted that implant 300 is only one example of a dental implant. Other types of dental implants and implantable prosthesis known in art can be treated using the method of the present invention. The implant in FIG 4, for example, has a coaxial threaded bore 308 in the center open at one end 310. A plurality of splines 312 extend upward from this end to interface with another component (not shown) such as an abutment. This spline interface has been disclosed in US Patent No. 5,449,291 entitled "Dental Implant Assembly Having Tactile Feedback."

[0084] Because other variations on the device and method of the present invention are possible within the scope of the claims, all items in the explanation and figures are for explanatory purposes only and do not limit the present invention in any way.

[Brief Explanation of the Figures]

[FIG 1] A partially cut away diagram of the reaction vessel in the first working example used embody the method of the present invention.

[FIG 2] A simplified diagram of the reaction vessel in the second working example used to embody the method of the present invention.

[FIG 3] A flowchart of the method of the present invention.

[FIG 4] A cross-sectional view of a dental implant with an HA coating treated using the method of the present invention.

[Explanation of the Reference Numerals]

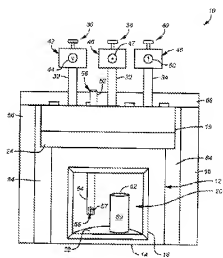
10, 100 ... Reaction Vessel
12, 102 ... Container
14, 104 ... Base
16, 106 ... Cover
18 ... Sidewall
20, 108 ... Cavity
22 ... Bottom Wall
24 ... Ring-Shaped Flange
26 ... Bolt
30, 32, 34, 150 ... Pipe
36, 38, 40, 126, 136, 152 ... Valve
50 ... Gauge
55, 182, 190 ... Thermocouple
60 ... Reservoir
64 ... Heating Jacket
66 ... Insulating Material
120 ... Water Line
122 ... Cooling Coil
124, 144 ... Flow Meter
130 ... Air Line
132 ... Compressor
134 ... Air Regulator

166 ... Rupture Disk

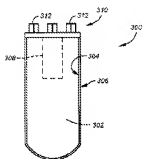
172, 174 ... Transducer

184, 192 ... Control Device

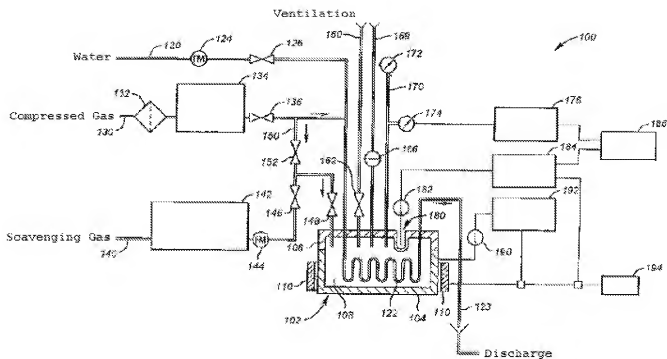
[FIG 1]



[FIG 4]



[FIG 2]



Key: 134) Air Regulator; 142) Gas Regulator; 176) Method Pressure Indicator; 184) Method Temperature Control Device; 186) Chart Recorder; 192) Surface Temperature Control Device; 194) Power Source

[FIG 3]

